the standard in safety

Overview of Internal Short Circuit Testing for Lithium-Ion Batteries

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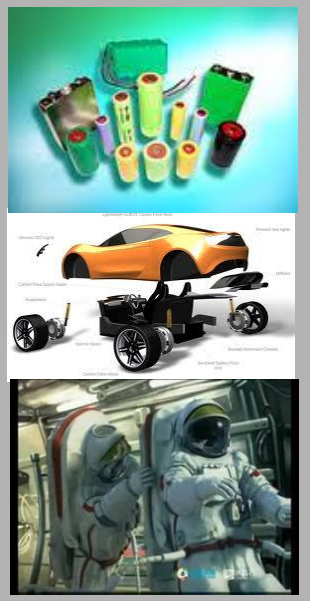
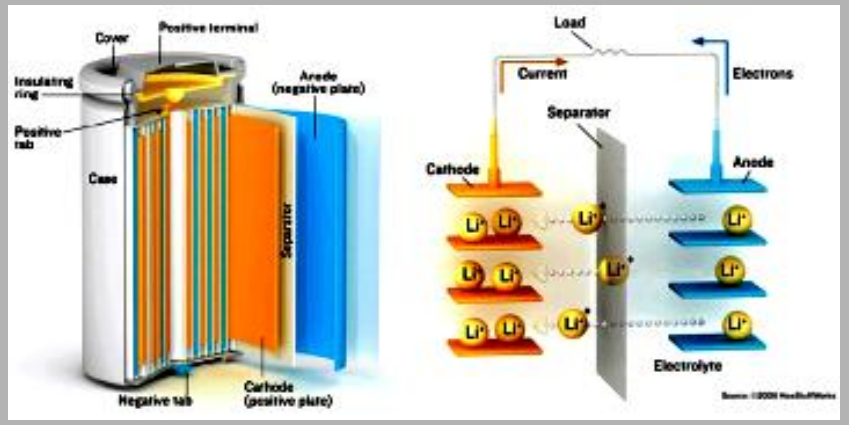


2010 NASA Battery Workshop

Outline

- Lithium-ion cell failures
- Battery safety standards
- Best practices for safety tests in standards
  - ***Hazard analysis – internal short circuit***
  - ***'Safe' failure***
- Lifecycle safety
- Looking ahead



Failure of Lithium Ion Cells

For products, such as batteries produced/consumed on very large scale (>10^6/yr), even with **6σ manufacturing processes**, a relatively large number of failures are inevitable.

This is not easily addressed by tests in safety standards

However, there is another aspect of failure of a commercial product that in normal use there are "reasonable and forseesable" abuse conditions that must be considered and ***these are affected by product design***.

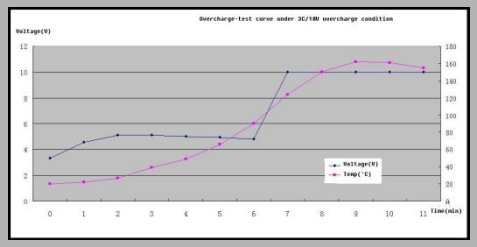
Developing comprehensive menu of abuse conditions is the main focus of tests in safety standards.

LiB Safety Standards Organizations

- Underwriters Laboratories Inc. (UL)
- International Electrotechnical Commission (IEC)
- National Electrical Manufacturer's Assoc. (NEMA)
- Society of Automotive Engineers (SAE)
- United Nations (UN)
- Institute of Electrical and Electronics Engineers (IEEE)
- Japanese Standards Association (JSA)
- Battery Safety Organization (BATSO)
- International Organization for Standardization (ISO)

Battery Safety Tests

- Impact
- Shock
- Vibration
- Heating
- Temperature cycling
- Drop
- Molded case heating
- Open circuit voltage
- Insulation resistance



- External short circuit
- Abnormal charge
- Forced discharge
- Crush
- Low pressure (altitude)
- Projectile (fire)
- Low rate charging
- Reverse charge
- Casing penetration
- Separator shutdown
- *Internal short circuit (TBD)*

Battery Standards Test Matrix

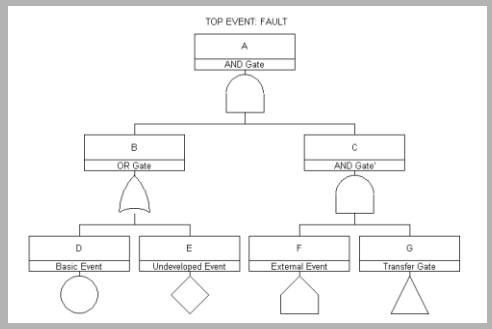
	UL					IEC		NEMA	SAE	UN	IEEE		JIS	BATSO
TEST CRITERIA\STANDARD	UL1642	UL2054	SU 2271	SU 2580	SU 2575	IEC 62133	IEC 62281	C18.2M,Pt2	J2464	Pt.III,S 38.3	IEEE1625	IEEE1725	JIS C8714	BATSO 01
External short circuit	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Abnormal charge	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Forced discharge	x	x	x	x	x	x	x	x	x	x	x	x	x	
Crush	x	x	x	x	x	x		x	x		x	x	x	x
Impact	x	x	x	x			x	x		x	x	x		
Shock	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Vibration	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Heating	x	x	x	x	x	x		x	x		x	x	x	
Temperature cycling	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Low pressure (altitude)	x		x	x	x	x	x	x		x	x	x	x	x
Projectile	x	x	x	x							x	x		
Drop			x	x		x	x	x					x	x
Continuous low rate charging						x							x	
Molded casing heating test								x						
Open circuit voltage								x						
Insulation resistance				x				x						
Reverse charge			x	x										
Penetration			x	x					x					
Separator shutdown integrity									x					
Internal short circuit test	*			*									x	

Internal Short Circuits (ISC)

- Current research focus of key battery safety research organizations
  - → ***ISC in lithium-ion cells (modules/packs)***
    - NASA
    - Argonne National Laboratory (ANL)
    - Sandia National Laboratories (SNL)
    - Oak Ridge National Laboratory (ORNL)
    - National Renewable Energy Laboratory (NREL)
    - Industrial Technical Research Institute (ITRI Taiwan)
    - National Taiwan Univ. of Science & Technology (NTUST Taiwan)
    - Universities (University of Hawaii, NTUST)
- Safety Standards Development organizations must help transition and translate this research into suitable tests
  - → ***Best Practices for Safety Tests***

Safety Tests Best Practices

- **Simple**
  - ✓ Minimize procedural and equipment complexity
  - ✓ R&R (Gage studies)
- **Intact Product**
  - ✓ Avoid disassembly of product
- **'Safe' failure**
  - ✓ Ensure safeguards in place
- **Data Driven**
- **Quantitative *and* Meaningful Metrics**
  - ✓ Qualitative better than *false* quantitative
  - ✓ Grounded in a strong hazard analysis framework
  - ✓ Pass/fail vs. screening approach



Hazard Analysis

- Standards safety tests need to be developed in the context of a ***hazard analysis:***
  - ✓ **Comprehensive**
  - ✓ **Based on multiple methodologies (FTA, FMEA, ETA, etc.)**
  - ✓ **Quantitative vs. Qualitative**
  - ✓ **Living document**

- Each safety test should address a root cause for a **particular failure mode**

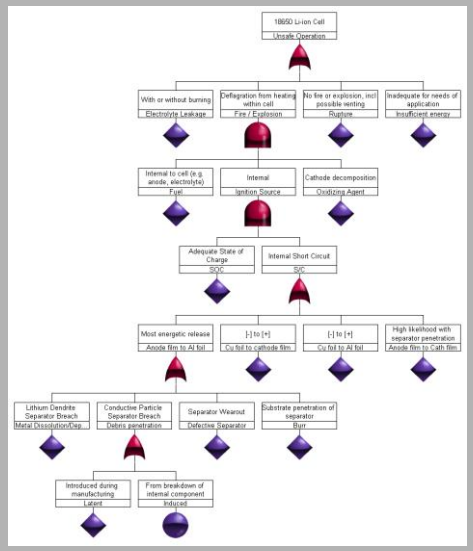
- For a failure mode that occurs at very low levels, a pass-fail test may not be adequate. Instead a test that induces failure and evaluates the subsequent performance may provide a more **risk-informed approach**.

Safety FTA (Top-Down)

- Guides development of tests in the safety standards
- Additional FTA considerations in the design of tests
  - ➢ *Multiple Occurring Event*
  - ➢ *Common cause failure*
  - ➢ *Primary vs. Secondary failure*
  - ➢ *Multiple Occurring Branch*

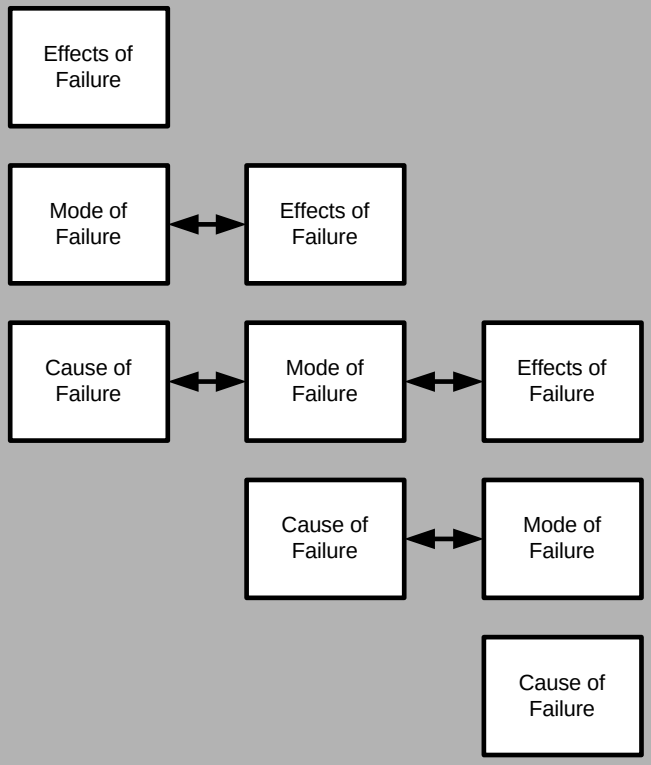
INTERNAL SHORT CIRCUIT

- **External force**
  - *Crush*
  - *Indentation (BNC, Pinch test, SISC)*
  - *Penetration (Nail)*
  - *Vibration*
- **Internal Defect**
  - *Manufacturing (IEEE)*
  - *Simulated (FISC)*
- **External Heat**



Safety FMEA (Bottom-Up)

SYSTEM ⟷ SUBSYSTEM ⟷ COMPONENT



Safety Failure Mode and Effects Analysis (S-FMEA)

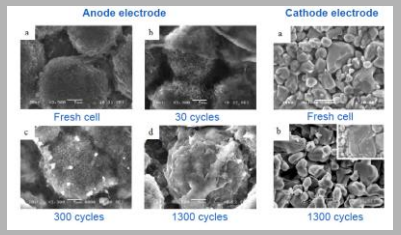
System/Component: **Separator - Lithium Ion 18650 Cell** Prepared by: **Anura Fernando**
Creation Date: 1/12/2010 **Rev Date: 1/25/2010**
Core Team: **Anura Fernando, Harry Jones, Mahmood Tabaddor, Alvin Wu**

Item / Function / Requirement	Potential Failure Mode	Potential Effect of Failure	Potential Cause(s) of Failure	SEV	Occurrence	Current Design Controls Prevention	Current Design Controls Detection	DET	RPN
Separator for 18650 Lithium Ion Cell Prevents the uncontrolled flow of electrons from anode to cathode while allowing lithium ions to pass through for charging	Failure of separator to prevent uncontrolled flow of electrons from anode to cathode resulting in short circuit and thermal runaway	Burns and injury to users, damage to components, property, environment	Lithium dendrite growth causing penetration of separator						
			Penetration by conductive contaminant particle introduced during manufacturing or produced by internal component degradation				Forced Internal Short Circuit Test		
			Defective Separator			Robust separator design	Subject 2591 Permeability, Thickness, Material consistency,Tensile Strength, Penetration Strength, Dimensional Stability,Shutdown Temperature, Melt Temperature		
			Non-penetrating xternal Force leading to compromised separator functioning				Blunt Nail Crush Test SISC Test		
			Penetrating external Force leading to compromised separator functioning				Nail Penetration Test		

Safety tests in standards serve as design detection in design FMEA

Hazards over Lifecycle

- New vs. aged cell samples
  - **Are aged cells more susceptible to a particular failure mode?**

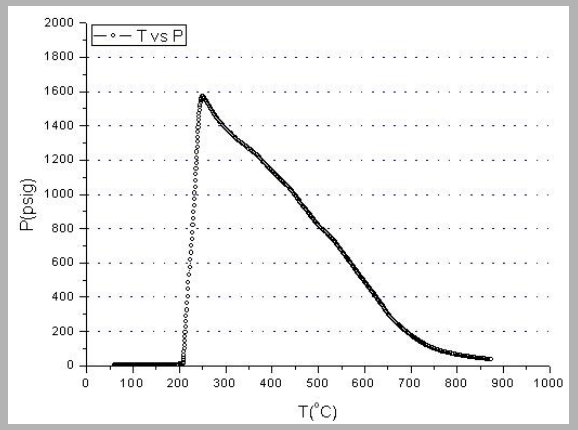


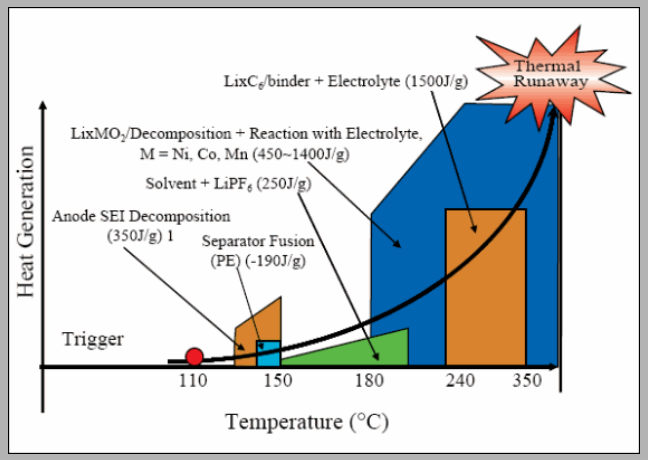
- Bulk transport and storage
  - **Concerns by insurance companies**
  - **Fire incidents on board freight airlines involving bulk transport of lithium-ion cells (FAA)**

- Disposal/Reuse/Recycling
  - **2nd life/secondary market for EV batteries as energy storage devices for utility systems**

‘Safe’ Failure

- **Adiabatic Reaction Calorimetry**
  Accelerating Rate Calorimeter (ARC)
  - Bench-scale apparatus for measuring runaway chemical reactions
  - Sample: 18650 lithium ion cell, 100% SOC
  - Heat source: 400 W



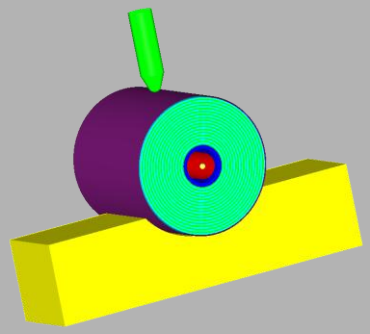


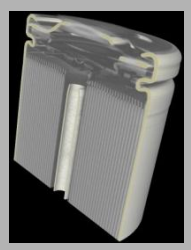
Source: Industrial Material Magazine, 264, 12/2008, pp.118-122

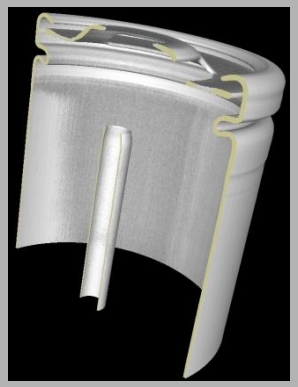
Sample	Weight, g (Before/After)	T_0, °C	$T_{max,s}$, °C	$P_{max,s}$, psig	T_{AD}, °C
Li-ion cell 4.3V, 2.6A, SoC 100%	46.2228/ 34.6095	138	875	1,574 at 262 °C	737

Looking Ahead

- Difficult challenges lie ahead for developing new internal short circuit tests (lithium-ion cells) suitable for safety standards
  - ***Standards are consensus based***
  - ***Product development is still cutting edge research***
  - ***Difficulties in procuring samples especially as testing moves from cell to module to pack***
- Transition of research laboratory safety test into a suitable format for standards
  - ***Based on best practices template***
  - ***Suite of tests for ISC depending upon product design and cause of failure***
  - ***Induce failure* versus *measure against a threshold***
  - ***Partnerships are vital***







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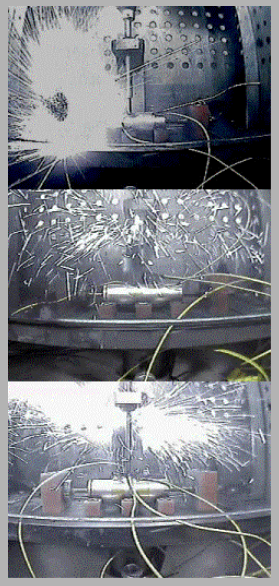

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